# The North Crater Neighborhood: more complex than Mr. Rogers'

**A discussion of cinder cones, lava flows, and rafted blocks**

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**Craters of the Moon National Monument and Preserve**

## Introduction

The area around North Crater cinder cone and the visitor center is one of the more complex areas in the Craters of the Moon lava field. About 2300 years B.P. this area may have looked very different than it does today. North Crater and the small flank cone on the southeast side of Sunset Cone may have been larger, and another cone or cones may have existed to the north of North Crater (see Fig. 1). Five lava flows, the Highway, Devils Orchard, Serrate, Big Craters Northeast, and North Crater flows, erupted from vents in the area. Three of these flows, the Highway, Devils Orchard, and Serrate flows, are particularly high in silica (54-64 wt%, Kuntz and others, (1986)) and were viscous enough to break apart cinder cones and carry the pieces as far as 13 km to the northeast (see Fig. 2). These pieces of broken cinder cones, carried by lava flows like icebergs in ocean currents, are termed rafted blocks. Considerable uncertainty remains regarding the existence of now absent cinder cones, the duration and timing of the lava flows, and the process of block rafting.

## Recent history of the North Crater Neighborhood

The Highway flow is the oldest lava flow in eruptive period A (about 2300 to 2000 years B.P.) to issue from the North Crater neighborhood (Kuntz and others, 1989). (See Fig. 2 for lava flows of the North Crater neighborhood and their spatial relations.) This block and a'a flow may have rafted away pieces of North Crater, or a northern cousin of North Crater, which are presently buried by younger flows. Considerable debate surrounds the origin of the Highway flow since stratigraphic relations between it, rafted blocks, and more recent flows are difficult to determine in many places. Kuntz and others (1982) offer two explanations.

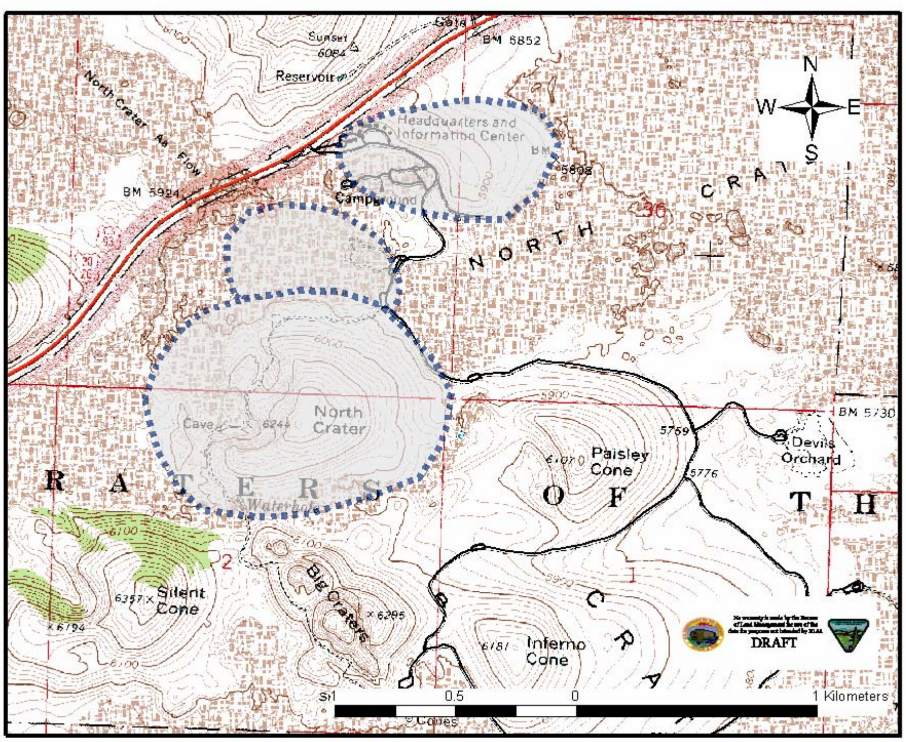



**Figure 1:** Portion of topographic map showing extent and location of North Crater and possible cousins of North Crater prior to block rafting events.

Briefly, in the first explanation, the Highway Flow flows north down the slopes of a then much larger North Crater or nearby cousin of North Crater. The viscous block flow then tears apart North Crater and begins to flow to the southeast, carrying much of the cone with it. The other explanation presented in Kuntz and others (1982) describes the Highway Flow erupting from a vent on the north side of the current Highway 20-26-93 to form a steep-sided tholoid. In this case, the lava flowed to the southeast throughout its history and did not reverse directions. I support this explanation over the first. In either case, it is quite possible that the Highway Flow rafted away pieces of a large North Crater, a cousin of North Crater, and or Sunset Cone's southeast flank cone.

Next, the Devil's Orchard block-a'a flow erupted from vents in the North Crater neighborhood, rafting blocks to the east. The Devils Orchard Nature Trail affords views of the many rafted blocks in the within the Devil's Orchard lava flow. Cinders erupted from North Crater after the Devils Orchard flow, masking much of the flow and the rafted blocks it carried.

Then, the Serrate block-a'a flow erupted, burying the northern margins of the Devils Orchard flow. The Serrate flow rafted a tremendous number of blocks to the east and northeast, some nearly thirteen kilometers from North Crater (see Fig 2). Many blocks began to disaggregate and mix into the Serrate flow as it carried them. The Serrate flow likely rafted blocks from the nearby cousin(s) of North Crater and breached North Crater itself.

Figure 2: Map showing extent of lava flows and the location of northeastern most rafted blocks.

Little is known about the Highway fault but the Serrate flow was so voluminous it may have contributed to the formation of the fault. Magma chamber recharge might not have kept pace with the rapid rate of eruption needed for such high silica flows to be emplaced and the North Crater neighborhood collapsed into the void, the displacement being recorded on the Highway fault.

Next, a series of three pahoehoe flows covered much of the block-a'a flows containing rafted blocks and the presumed vent areas for these block-a'a lava flows. First, the Big Craters Northeast flow buried much of the proximal Devils Orchard and Serrate flows. Then, the North Crater flow erupted from vents in the breach in North Crater, burying parts of the Big Craters Northeast flow. Finally, the Blue Dragon erupted from several vents along the Great Rift and obscured much of the distal Devils Orchard and Serrate flows.

Paleo North Crater Reconstruction

As part of an undergraduate thesis completed at Whitman College in May 2003, I attempted to reconstruct the breach in North Crater by adding up all the rafted material presumed to have come from North Crater. An approximation of the volume of material rafted from North Crater can be made by adding up the volumes of rafted blocks. A number of complications arise in determining this calculation. The depth below the surface that partially buried blocks extend can only be estimated. Where the rafted blocks maintained a discrete form as they rafted, generating a volume calculation is relatively simple. However, in some areas, blocks broke up as they were transported, creating domains of disaggregated rafted material that have been largely incorporated into the transporting Serrate Flow. An unknown number of blocks were partially or fully buried by as many as four later flows, depending on location. I devised methods to determine the depth to which blocks extend below the surface and determine the amount of rafted material in disaggregated domains. Since there is no way to estimate the volume of rafted blocks that are buried by lava flows, any calculation of the volume of material rafted from North Crater is likely a minimum estimate.

**Previous Studies**

Other than the geologic maps produced by Kuntz and others (1989), little work has been done to describe the block rafting events at Craters of the Moon National Monument and Preserve (COMNMP). Several authors working in other areas have described rafted volcanic blocks related to breached cinder cones but offer little insight into the details of their origin and transport (Foshag and Gonzalez, 1956; Simons and others, 1966; Holm, 1987). The notable exception is Harwood (1989), who studied breached cinder cones in the San Francisco volcanic field of north central Arizona. He offers three models for cone breach, (1) lava lake model; (2) dike intrusion model; and (3) magma body intrusion model. Harwood (1989) also describes five local controls on breaching mechanisms: (1) local topographic stress regimes; (2) local fault/joint system control; (3) wind direction/cone strength; (4) vent location of breaching lava; and (5) substrate buttressing. Searches in the literature for methods of reconstructing breached cinder cones and estimating their pre-breach volume were unsuccessful.

Field Work

The transporting block-a'a trachyandesite flows exerted tremendous stresses on the rafted blocks and the blocks shed unconsolidated ash, cinders, and spatter, disaggregating as they moved. The transporting flow incorporated the disaggregating cinder cone material particularly well between three and seven kilometers from North Crater. Foot travel in these areas is quite precarious and slow, limiting the ease of fieldwork. In some locations, as much as 100% of the surface of the lava flow is blanketed by a layer of disaggregated rafted blocks. More commonly, the transporting lava flow contains domains where 30-50% of the lava flow is disaggregated rafted blocks from North Crater (see Fig. 3).

In the 1980s, the U.S. Geological Survey (USGS) mapped large, discrete representative blocks which had maintained their shape in these areas. I visited the blocks, measuring their sub-aerial heights for later volume calculations. I recorded the area of each block from digitized geologic maps viewed in ArcView (ESRI, 1999). The typical length, typical width, and max height of discrete, coherent rafted blocks which were not included on USGS geologic maps were also measured and their position recorded with GPS by Glenn Mutti (National Park Service, Geologist in Park, summer 2002) or myself as part of a larger study of geologic resources of COMNMP.

**Volume of Discrete Blocks**

I calculated the volume of previously unmapped discrete rafted blocks which had not disaggregated by multiplying the typical length, typical width and maximum height of each block together. The areas of blocks mapped by the USGS were multiplied by heights measured in the field or taken from topographic maps. The volumes of all the blocks were then summed.

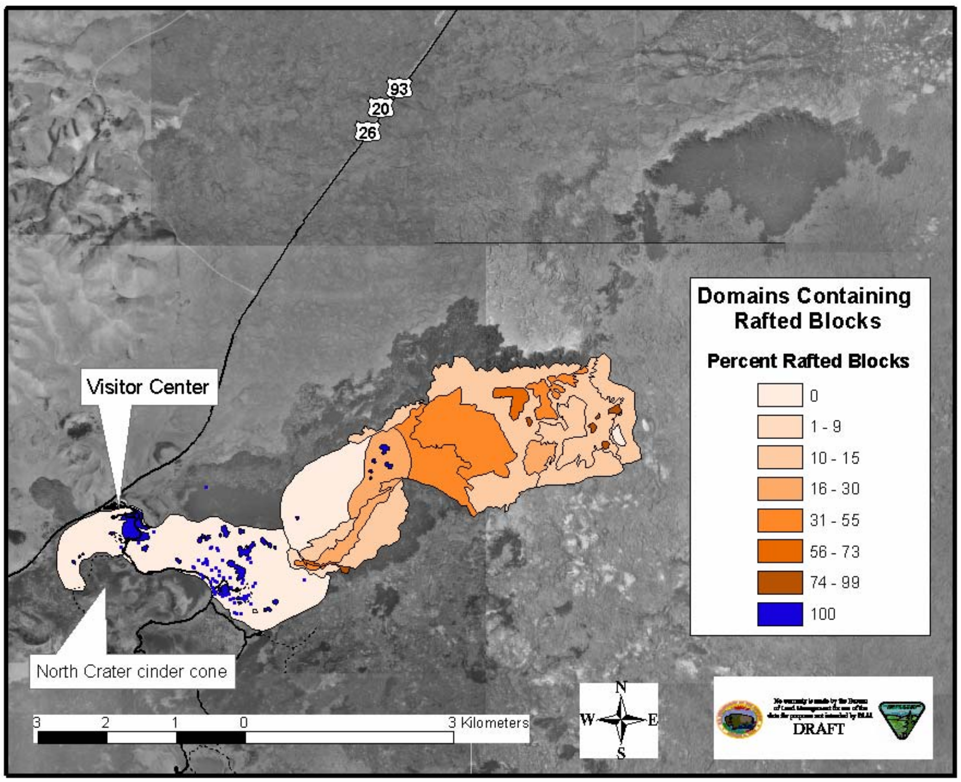



**Figure 3:** Digital air photo showing the locations of domains of disaggregated rafted material.

**Volume of Disaggregated Blocks: The Domain Approach**

The volumes of disaggregated blocks were determined with the help of ArcView (ESRI, 1999). Domains of varying percentages of rafted material were identified by examining stereo air photos and delineating the extent of the domain on digitized air photos in ArcView (see Fig. 3). I estimated the percent rafted material in each domain after careful examination of stereo air photos and review of field notes. Domains where rafted material was buried by younger pahoehoe flows were assigned percentages of rafted material from the most appropriate nearby domain, if one existed.

I developed a method to add up all the disaggregated cone material, creating an equivalent area that the disaggregated cone material would occupy if it were all put back into a coherent block (see Fig. 4). By multiplying the area of a domain, the percent of rafted material within it, and the maximum height of blocks in the domain together, the total above surface volume can be determined. The sub-surface volume is accounted for by multiplying by the correction factor for the coherent block roots determined in the density analysis discussed below. Since an unknown amount of material is buried by younger flows, and lost within the transporting flow, any calculation will likely be a minimum.

**Correction Factor for Sub-surface Roots of Blocks**

There are two possibilities for the subsurface volume of blocks in disaggregated domains. The first is that there are no "roots" to the disaggregated blocks. As the blocks rafted and broke up, their mass decreased and they rose isostatically until they were completely disaggregated. In this scenario, there are no subsurface (>2 m deep) coherent rafted blocks; the entire block was broken up and partially incorporated into the transporting flow. The second possibility is that the transporting block a'a lava flow was viscous enough to retard the isostatic rebound forces generated by the reduction in the block mass from disaggregation leaving a block "root" buried at some depth beneath the surface of the flow. This scenario is favored from field observations and implicit in the calculations described below.
By comparing the specific gravities of the transporting trachyandesite lava and the rafted block material, the depth to which the blocks sink in the transporting flow (like the isostasy of icebergs floating in the ocean) can be determined and a complete volume can be calculated (see Fig. 5).

| Determining the amount of rafted material in each domain | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | coherent block equiv area of disaggregated blocks | | | | | |
| A<br>Domain ID number | B<br>amt transport flow, no rafted material (% area of domain) | C<br>amt rafted discrete blocks (% area) | D<br>(%) area that is disaggregated rafted material | E<br>amt of D actually cone material (%) | F<br>thickness (m) | G<br>height of coherent blocks in domain (m) | H<br>total % rafted material if were coherent blocks | comments<br>H = ((d x e x f)/g)+ c (Note: colums B,C, and D should sum to 100;block heights in bold are from field measurment) |
| 52 | 10 | 40 | 50 | 90 | 2 | 7 | 53 | Used block height for 32; seems too short |

**Figure 4:** Portion of chart showing method used to determine the coherent block equivalent of disaggregated blocks in a domain.

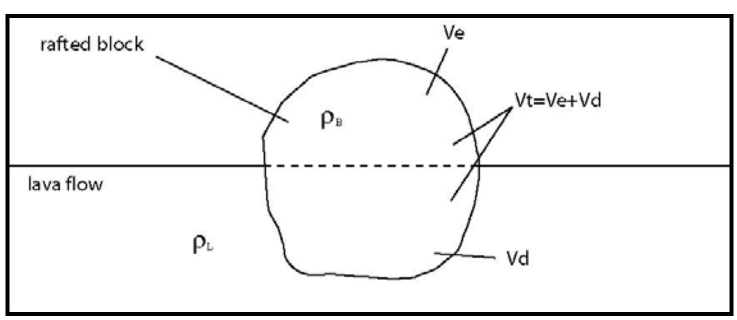


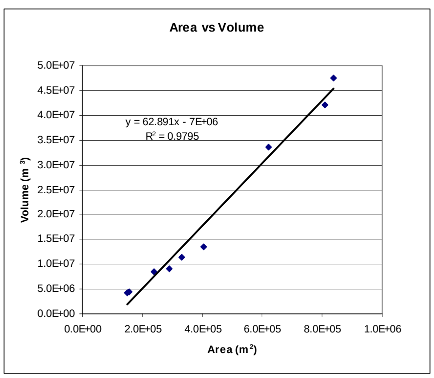

**Figure 5:** Sketch showing rafted block being transported by lava flow and block "roots" where $\rho_B$ is density of rafted block, $\rho_L$ is density of transporting lava flow, $V_D$ is volume of the displaced lava, $V_E$ is volume of exposed portion of block, and $V_T$ is total volume of rafted block.

According to equation 1, $\left[\rho_{lava} \div \left(\rho_{lava} - \rho_{block}\right) = \left(V_t \div V_e\right)\right]$ the total volume of rafted material ($V_t$) can be determined from the volume of exposed rafted material ($V_e$) and the densities of the transporting lava ($\rho_{lava}$)and rafted blocks ($\rho_{block}$).

I calculated the specific gravity of the rafted blocks by completely immersing samples in water and recording the volume change. The mass of the sample was divided by its volume. Samples were shrink wrapped to prevent water from entering the vesicles but this was only marginally successful. Nevertheless, I was able to correct for the water trapped in the vesicles by reweighing the sample after immersion. The densities of the Devil's Orchard and Serrate transporting flows were calculated using major-element analysis data from Kuntz and others (1985) in MAGMA software (Wohletz, 2002).

**Digital Elevation Models**

In order to compare the calculated volume of a "paleo North Crater" to the volume of other cones at COMNMP, the relationship between the area of a cone's footprint, its volume, and height were analyzed (see Fig. 6). Utilizing Mila Grid Utilities and Xtools extensions in ArcView (ESRI, 1999) and ten meter grid USGS Digital Elevation Models (DEMs), I examined eight fairly symmetrical un-breached cinder cones within Craters of the Moon lava field. Data analysis was completed in Microsoft Excel. The models were also useful in determining the volume of the modern North Crater had its northwest side not been breached.



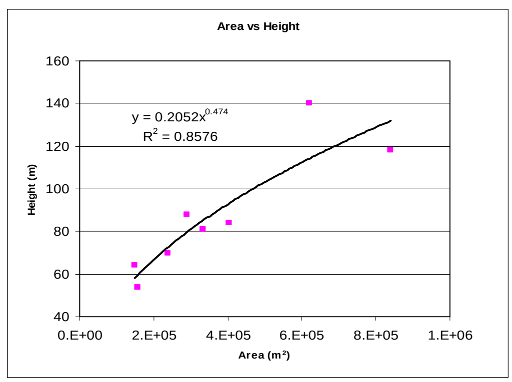




**Figure 6:** Graphs of Area vs Volume) and Area vs Height from DEM analysis of intact cinder cones. All units are meters.

**RESULTS:**

Based on the methods described above, the volume of rafted material above the surface was calculated to be 21 x $10^6$ $m^3$. Consideration of the density analysis and correction factor for the subsurface "roots" of coherent discrete blocks gives a more complete picture of the volume of rafted material.

I calculated the average specific gravity of the rafted blocks to be 1.42 g/$cm^3$ and estimated from major element analysis of the lava flows (Kuntz and others, 1985) and MAGMA software that the density of the Serrate and Devil's Orchard flows ranges between 2.59 and 2.82 g/$cm^3$. Plugging these numbers into equation 1 shows the ratio of total volume of rafted material to volume of rafted material exposed at the surface ranges between 2.01 and 2.21.

Multiplying by the correction factor of 2.15 (the average of the two end members) recovers the subsurface rafted material and gives the total rafted material: 46 x $10^6$ $m^3$. Using the relation between cone footprint area and cone volume, as well as the current volume of North Crater, I determined that the breach in the northwest side of North Crater is only $1.23 \times 10^6$ $m^3$. My calculations show there is over 38 times more rafted material than fits back into the hole in North Crater. Putting the $46 \times 10^6$ $m^3$ of rafted material back onto the current North Crater would create a paleo-North Crater with a volume of $88 \times 10^6$ $m^3$, a footprint area of $1.52 \times 10^6$ $m^2$, a radius of 697 m, and a height of 175 m.

### Error

Despite any errors which may have resulted in overestimation of the amount of rafted material (in particular rafted block densities too high and percent rafted material in domains too great), the value of rafted material calculated is probably still a minimum. Perhaps as much as half the area which could contain rafted blocks is covered by younger lava flows which obscure any rafted blocks which may be there. In the summer of 2003, I found additional rafted blocks not included in my initial study. I confirmed that an area over 4 $Km^2$ not included in the original analysis contained rafted blocks. I had previously speculated rafted blocks existed in this very remote area but had no air photos or geologic maps to confirm their existence and quantify their volume.

## DISCUSSION:

The reconstruction of North Crater presented above results in a paleo-North Crater that is substantially bigger, 40 m higher with a radius nearly 200 m larger, than the current North Crater. This paleo-North Crater is quite large but still reasonable since cinder cones of this size exist today in the lava field. For example, paleo-North Crater would have been approximately the size of Big Cinder Butte, 4 km to the south of North Crater.

An alternative explanation to the large, monogenetic cone model is the presence of other, smaller monogenetic cinder cones that were rafted away. These cones may have been parasitic or flank cones, utilizing the same magma chamber and plumbing system as North Crater. Alternatively, they may have been completely different cones having different vents and magma plumbing systems. Confirmation of these cones' existence is difficult because lava flows from North Crater, or other vents, may have rafted them away and younger flows have buried any evidence. The possible cinder cone deposits near the highway and campground may be remnants of past neighbors to North Crater.

Another potential explanation is provided by Foshag and Gonzalez (1956). They observed the development, destruction, and subsequent reconstruction of cinder cones throughout the early eruptive phases of the Parícutin volcano in Mexico. This repeated breaching and repair of cinder cone walls could generate substantially more material than would fit in the existing hole in North Crater. Foshag and Gonzalez (1956) witnessed cone breaching, block rafting, and repair of the breach on the time scale of months and sometimes weeks. The presence of rafted blocks within two distinct lava flows (the Devil's Orchard and Serrate flows) suggests that at least two distinct periods of cone breaching, block rafting, and probably repair, took place over time. Instead of paleo-North Crater being one large, monogenetic cone, several smaller paleo-North Craters, perhaps similar in size to the present one, may have formed and been completely destroyed.

### Models for Cone Breaching

Much more field work needs to be completed to conclusively utilize Harwood's (1989) three models for cone breach (lava lake, dike intrusion and magma body intrusion) but I speculate that all three models have importance in the breaching of North Crater. The high percentage of spatter in the rafted blocks and in the intact portions of the cone may suggest the intermittent presence of a lava lake within the cone.

This lava lake may have overtopped the cone, flowing down the cone flanks, tearing apart North Crater. In addition, the breach has areas of spatter which accumulated, over steepened, and slid as coherent blocks down to the base of the cone. Nearly all breached cinder cones at COMNMP have breaches which align in a NNW-SSE azimuth roughly parallel to the axis of the Great Rift. Dike intrusion, related to the regional extension causing the Great Rift, along this NNW-SSE azimuth would weaken the cone, making it more susceptible to gravitational collapse from its own weight as well as the weight of a lava lake within it. Furthermore, the high number of vents in the North Crater neighborhood, both on and near the Great Rift, suggests that a large magma body might have underlain much of the area and intermittently found its way to the surface.

### Controls on Breaching

Of the five local controls on breaching mechanisms Harwood identifies, four may have played a significant role in the breaching of North Crater: (1) local topographic stress regimes; (2) local fault/joint system control; (3) wind direction/cone strength; and (5) substrate buttressing. If one particular side of the cone accumulated more spatter, the topographically induced stress regime there would change. The extra weight of spatter at that location might initiate gravitational collapse. That nearly all breached cinder cones at COMNMP have breaches that lie parallel to the axis the Great Rift and Basin and Range extension suggests that local fault/ joint system control is also important. Prevailing wind direction/cone strength and substrate buttressing are related to each other and have significance in the breaching of North Crater. Because the prevailing wind is generally from the west, pyroclastics accumulate on the east side of the cones, strengthening them. The west sides are generally steeper and might therefore be more susceptible to gravitational stresses whereas the east sides slope more gently because the wind spreads the pyroclastics out, creating a lower angle, more stable buttress.

## CONCLUSION:

Reconstruction of North Crater by adding the volume of material rafted from North Crater to the current North Crater creates a paleo-North Crater that is much larger than the breach in the northwest side of North Crater can contain. The volume of rafted material is $46 \times 10^6$ $m^3$ and the breach in North Crater is only $1.2 \times 10^6$ $m^3$. Adding the rafted material ($46 \times 10^6 m^3$) to the current North Crater ($42 \times 10^6$ $m^3$) suggests Paleo-North Crater may have been as large as $88 \times 10^6$ $m^3$. The radius and height of this large paleo-North Crater would have been nearly 200 m greater and 40 m higher than the modern North Crater. It would have extended from North Crater's current position north to Highway 93 and east to the campground. Since North Crater has a prolonged and complex eruptive history, it is more likely that several smaller paleo-North Craters and cousins of North Crater existed through time, each being built, partially or completely destroyed by rafting events, and then rebuilt.

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